Distribution of Organic Matter and Plant Nutrients in a Plantation of Scots Pine

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FOREST MANAGEMENT is becoming more intensive and soil fertilization is being advocated as a means of increasing forest productivity and of maintaining soil fertility. Investigations of problems of forest production and nutrition need to consider all the components of woodland communities but since forest ecosystems are variable and multi-layered structures they are difficult to sample accurately. Few data have been published showing the distribution of organic matter and nutrients within forest stands. The purpose of this account is to present such data for a plantation of Scots pine (*Pinus sylvestris* L.) and in so doing to indicate some of the difficulties encountered in sampling forest ecosystems.

Sample Plot

A rectangular plot, 20m by 25m, was marked out for sampling in a 12-acre forest compartment, at about 550 feet above sea level. The compartment forms part of the extensive coniferous plantations near the town of Jedburgh in southern Scotland. The climate is mild with an average annual temperature of about 46°F and an annual precipitation of approximately 30 inches. The soil, a heavy clay of the Hobkirk Series, is only moderately freely drained and of low base status (Muir, 1956).

Previously the area was covered with a mature woodland of Scots pine with trees 80 to 100 years old but this was clear felled in 1916. The present woodland was planted in the spring of 1924 by notch planting 2-2 seedlings of Scots pine at 3½ x 4 feet spacing. After planting, the woodland received little attention because of labor shortage so that the present stocking density has resulted mainly from the natural suppression of the less vigorous trees.

The plot contained the following living trees, 213 Scots pine, 18 birch and 1 oak, the birch and oak having established themselves naturally in the young pine plantation. In addition, there were 118 standing dead trees many of which were supported by the crowns of the surrounding trees because of the high stand density.

In October 1956 all living trees in the plot were measured for top height, bole girth at breast height and various canopy dimensions such as depth and spread of crown. The Scots pine had an average height of 49 feet and an average bole girth of 1 foot 2 inches. The sample stand would be of quality class II according to the yield tables prepared by Hummel and Christie (1953) but the lack of thinning has probably resulted in a different height and girth than might have been recorded if the plantation had been managed more actively.

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Methods

Sampling was restricted to pine trees since the birch and oak were relatively small and few in number. In the sample plot 207 of the 213 pine trees had boles with girths greater than 6.5 but less than 21.5 inches, i.e. within ± 7.5 inches of the average girth. The girth range was divided into five equal classes 6.5 to 9.5, 9.5 to 12.5, 12.5 to 15.5, 15.5 to 18.5 and 18.5 to 21.5 inches, the central class including trees of average girth. The girth classes are designated A, B, C, D and E respectively for simplicity of reference and their mid points are roughly equivalent to bole diameters at B.H. of 3.2, 3.7, 4.2, 4.6 and 5.0 inches.

In March 1957, the sample plot was quartered into corner quadrats and one tree of each of the five girth classes was marked for examination in each quarter, making a total of 20 trees, four of each girth class in the entire plot. The bole girth of a selected tree was always at the mid-position of the girth class it represented.

All 20 trees were felled and the roots of 17 were carefully excavated, by hand digging and winching, down to a diameter of half a centimeter. Roots with a diameter of less than half a centimeter were called rootlets and were not sampled separately for individual trees but were collected for the plot as a whole by taking eight soil cores of known volume and separating out the rootlets later. The weight of rootlets are included in the root weights given in the tables. Random circular quadrats, 81 sq cm in area, were used to sample the ground flora and litter layers, 100 quadrats per quarter for the vegetation and 15 per quarter for the litter. The sample trees, vegetation, litter and soil cores were transported quickly to the laboratory. All dry weights are given as oven dry at 80°C. For chemical analysis, samples of the plant material were ground in a Christy and Norris mill to pass through a sieve with holes having a diameter of 0.4 mm. Nitrogen was determined by the micro-Kjeldahl technique. The mineral analysis was carried out after wet digestion of the ground plant material using nitric, sulphuric and perchloric acids. The sodium and potassium contents of the resultant acid solution were determined with a flame photometer, magnesium by the titan yellow and phosphorus by the molybdate-blue method using a Spekker absorptiometer and calcium by the versenate technique.

Individual Tree Dimensions

The sample trees do not include the largest and smallest trees in the plot yet still differ greatly in size and form even though they are of identical age and originate from the same group of seedling plants. For example, some of the sample trees have a bole girth more than double that of other trees. The pines in the larger bole girth classes are taller than those of the smaller girth classes and have more elaborate and extensive root systems (Table 1). The roots of the largest tree spread about twice as far laterally and downwards as the roots of the smallest tree and similar differences occur in the spread and depth of the living crowns (Fig. 1).

The sample trees also differ considerably in dry weight, the heaviest sampled tree being twelve times as heavy as the lightest (Table 2). Trees of larger bole girth tend to be heavier in all respects having greater weights of leaves, cones, living branches, boles and roots. Bole material accounts for most of the dry weight of the trees but the relative proportions of the tree components are not constant. The percentage weight of bole material tends to decrease as tree size increases and there are corresponding increases in the percentages of crown and root material (Fig. 2). The different structures of trees of different sizes may result partly from genetical variations but can also be attributed to environmental or chance factors favoring certain trees initially so that they grow relatively rapidly during the early years to attain a more favorable position which influences tree form.

Knowing the relationship between linear dimensions and the weights of the sample trees (Fig. 3), the weights of the remaining standing trees can be estimated from their height and bole girth measurements. Since tree height is sometimes difficult to measure accurately in dense woodlands and proved to be fairly closely correlated with bole girth, regression equations have been calculated relating tree weight to bole girth only (Table 3). Although some variation occurs between trees of the same girth class, the weights of the various tree parts are closely correlated with bole girth but the regression equations differ for different tree parts. In determining the total dry weight of individual trees, it is advisable to consider each component separately in order to avoid errors caused by the changing proportions of leaf, branch, bole and root material as the bole size increases. The weight of cones per tree is small and variable so that it has not been included in the estimates of tree weight and nutrient content.

Nutrient Content of the Trees

The concentrations of various plant nutrients in the leaves, branches, bole and roots of the sample trees were determined and the averages for each girth class are shown in Figure 4. The percentages of the nutrients decrease consistently in the order: leaves, living branches, roots and boles except that the percentage of calcium in the boles is larger than that of the roots. In most cases, the nutrient concentration also decreases as tree size increases so that 20 of the 23 linear correlations between tree girth and nutrient concentration are negative, ten significantly so (Table 4). Wright

TABLE 1. Dimensions of sample trees.

Tree number	Girth class[1]	Height	Number of whorls with living branches	Number of primary living branches	Total length of primary living branches	Number of main lateral roots	Length of longest root (over 0.5cm diameter)	Maximum root depth in soil
		m			*m*		*m*	*m*
1	A	8.9	11	28	13.6	2	0.7	0.4
2	A	10.4	12	28	15.3	5	0.8	0.4
3	A	9.3	10	27	11.7	3	0.7	0.5
4	A	9.5	12	33	18.8	7	0.9	0.5
5	B	10.1	10	30	20.1	Roots not sampled		
6	B	11.5	11	47	32.0	3	1.0	0.6
7	B	11.8	11	42	29.3	4	0.9	0.6
8	B	11.6	12	50	34.2	5	0.9	0.5
9	C	12.1	13	69	54.1	6	1.0	0.6
10	C	12.3	11	51	39.7	6	1.6	0.7
11	C	12.7	13	44	42.3	7	1.5	0.6
12	C	12.3	13	51	43.8	5	0.8	0.7
13	D	12.2	13	62	40.0	6	0.9	0.6
14	D	12.3	13	48	49.3	5	1.2	0.7
15	D	12.5	12	51	49.6	5	1.7	0.4
16	D	12.2	11	58	51.1	5	—	0.8
17	E	13.0	10	52	54.2	Roots not sampled		
18	E	12.6	16	83	89.6	Roots not sampled		
19	E	13.3	13	70	78.3	7	1.8	0.8
20	E	14.0	16	56	79.2	7	1.1	0.7

[1] Each girth class in terms of d.b.h. in inches is approximately as follows: A = 3.2; B = 3.7; C = 4.2; D = 4.6; and E = 5.0.

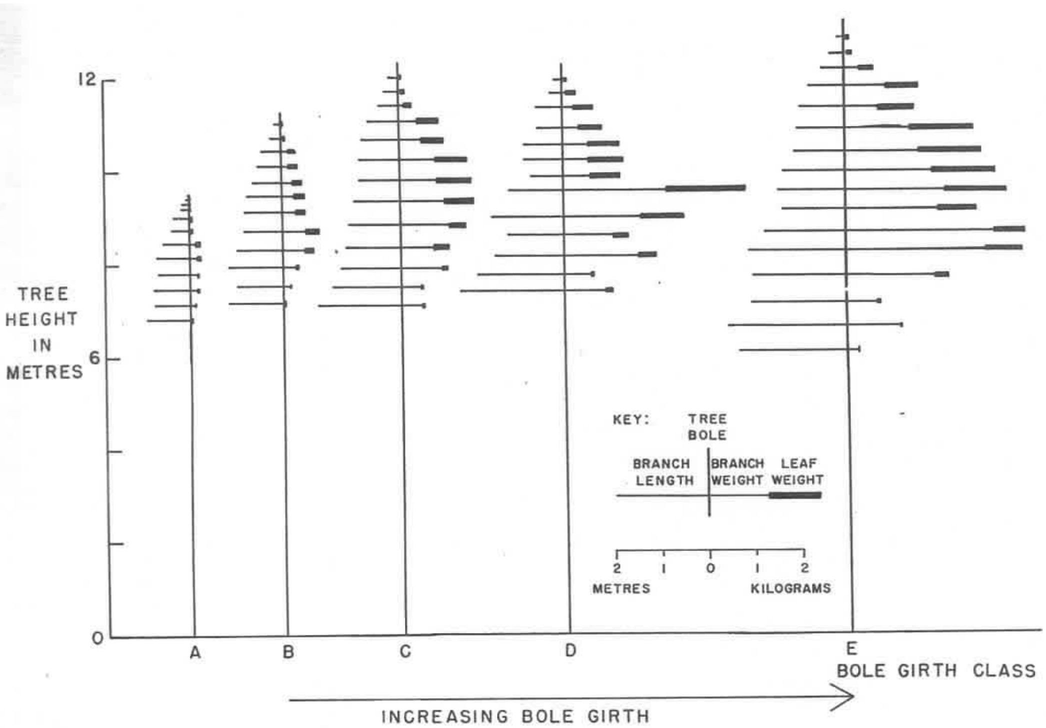

FIGURE 1. *The average whorl heights, branch length and fresh weights of branches and leaves for trees of different girth classes.*

TABLE 2. Oven-dry weights (Kg) of sample trees.

Tree number	Girth class	Leaves	Living branches	Cones	Bole	Living shoot	Dead branches	Roots
1	A	0.1	0.3	0	6.1	6.5	1.1	0.9
2	A	0.1	0.3	0	7.4	7.8	0.8	1.8
3	A	0.1	0.2	0	7.5	7.8	0.8	2.1
4	A	0.2	0.5	0	7.6	8.3	0.4	1.6
5	B	0.3	0.9	0	13.5	14.7	2.0	Not collected
6	B	0.8	1.1	0	15.2	17.1	0.4	3.3
7	B	0.8	1.1	0.01	16.2	18.1	0.9	3.5
8	B	0.6	1.3	0	16.8	18.7	1.6	4.5
9	C	1.3	3.0	0	24.1	28.4	2.0	6.6
10	C	1.5	2.4	0.01	27.9	31.8	1.5	6.9
11	C	1.8	4.0	0.02	28.9	34.7	3.1	7.0
12	C	1.9	2.4	0	30.7	35.0	1.4	7.0
13	D	2.6	2.9	0.04	34.5	40.0	2.2	7.3
14	D	2.9	5.5	0	38.0	46.4	2.8	12.7
15	D	2.7	4.7	0	40.7	48.1	5.0	13.5
16	D	3.0	5.1	0.04	41.5	49.6	4.3	8.1
17	E	2.9	4.9	0.02	52.6	60.4	3.6	Not collected
18	E	3.8	9.4	0.10	50.2	63.5	4.6	Not collected
19	E	4.6	10.0	0.01	56.5	71.1	5.8	19.2
20	E	4.4	11.8	0	64.0	80.2	4.0	18.1

and Will (1958) and Ovington and Madgwick (1959) have obtained similar results for pine and birch respectively but Leyton and Armson (1955) have recorded positive correlations between tree growth and foliar concentrations of nitrogen, phosphorus and potassium. Leyton and Armson sampled needles only from the uppermost whorls of Scots pine so that their results of foliar analysis are probably not representative of the whole leaf mass.

By combining the dry weight and percentage chemical composition data, the total weight of plant nutrients in the sample trees can be calculated and the averages for trees of each girth class are given in Table 5. The percentages of sodium in some bole samples were too small to be measured accurately by the analytical techniques used so that the weights of sodium in the tree boles are not given. The different concentrations of nutrients in leaves, branches, boles or roots result in a different weight distribution of nutrients as compared with dry matter within the trees. For example, leaf material represents 2 to 5 percent of the dry weight of the trees but contains 8 to 36 percent of the weight of nutrients. In contrast the tree boles usually constitute about three quarters of the total dry weight but contain less than half of the

TABLE 3. Regression equations for tree weights and bole girths.

Tree part		Standard error
Leaves	$\log_{10}W = 3.63 \log_{10}g - 2.57$	0.11
Living branches	$\log_{10}W = 3.52 \log_{10}g - 2.21$	0.12
Dead branches	$\log_{10}W = 2.08 \log_{10}g - 1.23$	0.18
Boles	$\log_{10}W = 2.23 \log_{10}g - 0.24$	0.04
Roots	$\log_{10}W = 2.60 \log_{10}g - 1.11$	0.10
Living tree (exclusive of rootlets)	$\log_{10}W = 2.47 \log_{10}g - 0.25$	0.05

W = oven dry weight (Kg).
g = bole girth at breast height (cm).

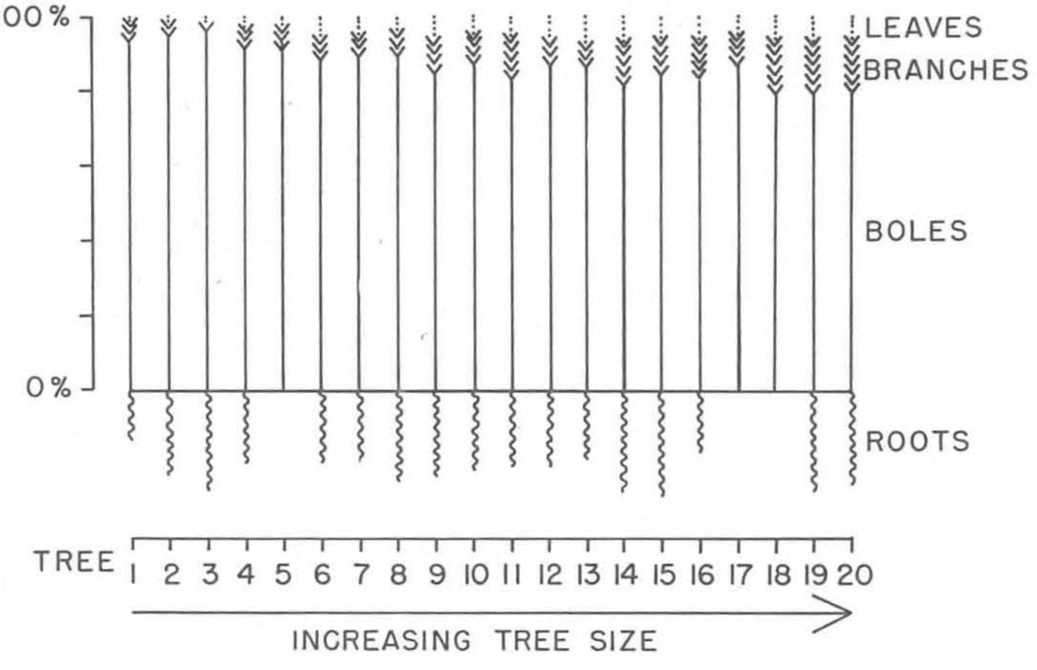

FIGURE 2. *The relative proportions of sample trees as percentages of the oven dry weight of the living shoot.*

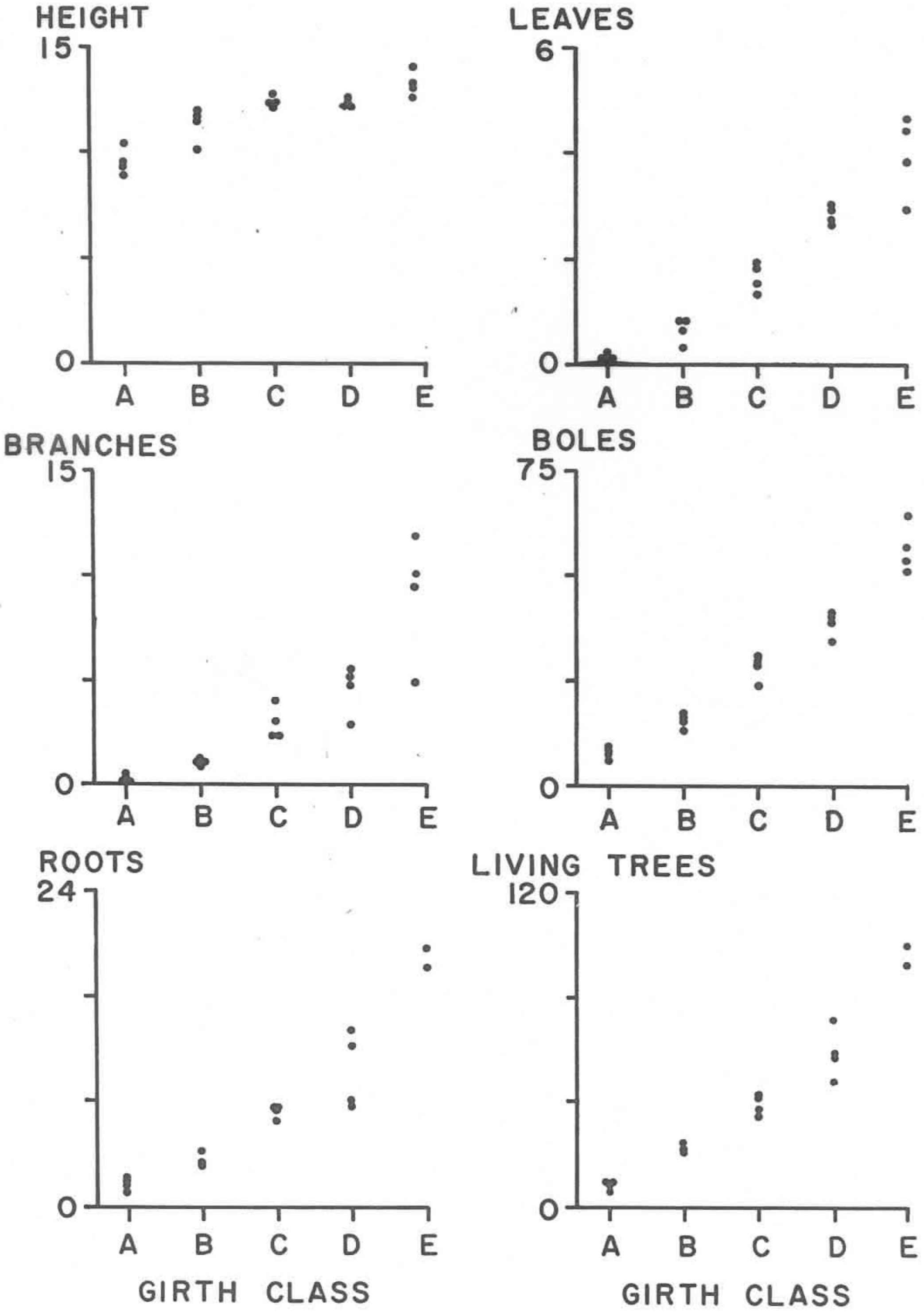

FIGURE 3. *The relationship between tree height (m), dry weight (Kg) of tree parts and bole girth class.*

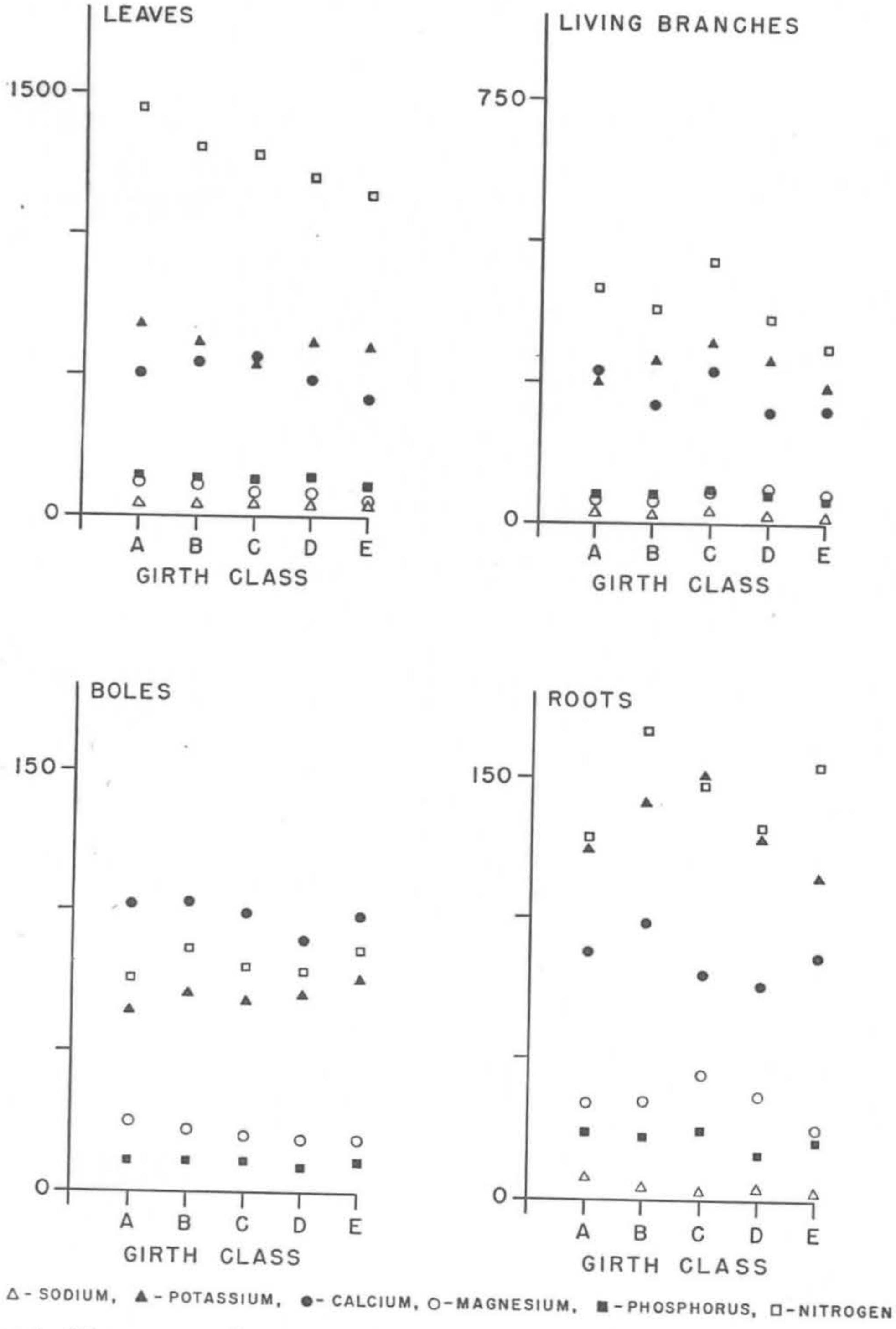

FIGURE 4. *The average nutrient concentration (mg/100g O.D.) of tree parts.*

TABLE 4. Correlation coefficients between nutrient concentration and bole girth.

	Leaves	Living branches	Boles	Roots
Sodium	−0.029	−0.377	----	−0.612**
Potassium	−0.263	−0.039	+0.387	−0.075
Calcium	−0.484*	−0.434*	−0.258	−0.319
Magnesium	−0.863***	−0.440*	−0.821***	−0.081
Phosphorus	−0.457*	−0.465*	−0.102	−0.409
Nitrogen	−0.663**	−0.442*	+0.211	+0.114

*Significant at the 5% level.
**Significant at the 1% level.
***Significant at the 0.1% level.

nutrients in the trees.

Although the percentages of nutrients in the smaller trees are greater than those in the larger trees, the differences in dry weight are so great that the larger trees contain a greater weight of plant nutrients. However, differences in nutrient content are not so marked as differences in dry weight, for instance the trees of the largest girth class carry over 30 times the weight of leaves on trees of the smallest girth class but their leaves contain only 10 to 25 times the amount of nutrients.

Weight and Nutrient Content of Tree Stock

The total dry weight and the nutrient content of all the pine trees in the stand can be estimated using three principal techniques. (1) Trees of average bole girth may be assumed to be of average dry weight and chemical composition so that the weights for the tree stock can be estimated by multiplying the average data by the number of trees in the stand. (2) Trees of average bole girth may be assumed to be of average dry weight and chemical composition for the girth class they represent. The totals for each class can be calculated by multiplying the average data by the relevant number of trees in each girth class. The plantation weights are determined by summing the results for each girth class. Unusually small or large trees outside the measured girth class range are included in the smallest and largest girth classes respectively. (3) The formula given in Table 3 can be used to calculate the weight and nutrient content of each tree from its bole girth. The weight of the tree stock is obtained by adding the individual tree data.

The dry weight of the tree stock has been calculated using all three methods and the results are given in Table 6. Comparisons of the three sets of dry weight data on an area basis show that method (1) gives consistently low results compared with methods (2) and (3), whilst method (2) tends to give slightly smaller values than method (3). Method (1) is undoubtedly the most unreliable of the three, for it is clear from the individual tree data that trees of average bole girth are not average in other respects so that a serious underestimate of the weight of the tree stock results. In fact a truly "average" tree does not exist in the stand since a tree of average bole weight would have a different bole girth to that of a tree carrying the average weight of leaves. The smaller values, particularly of bole weights, obtained by method (2) compared with those of method (3) are in part due to the sample trees not being representative of their girth class but are also due to the failure to account adequately for the few but relatively large trees occurring outside the sampled girth range. In the sample plot there were five trees having

TABLE 5. The average nutrient content (g) of sampled trees in different girth classes.

	Girth class				
	A	B	C	D	E
Number of trees	28 + 1	50	65	41	23 + 5
Sodium					
Leaves	0.07	0.23	0.67	1.01	1.72
Living branches	0.07	0.17	0.59	0.62	1.19
Dead branches	0.09	0.16	0.34	0.46	0.75
Bole	Too small to be determined by analytical techniques				
Roots	0.12	0.13	0.23	0.37	0.58
Potassium					
Leaves	1.0	3.8	8.5	17.1	23.6
Living branches	0.9	3.2	9.7	13.0	20.9
Dead branches	0.2	0.5	0.6	1.4	1.8
Bole	4.7	11.0	18.6	27.0	42.2
Roots	2.0	5.3	10.3	13.1	21.5
Calcium					
Leaves	0.8	3.5	9.1	13.6	16.4
Living branches	0.9	2.4	7.9	8.8	18.0
Dead branches	0.9	1.5	3.1	5.1	5.8
Bole	7.3	16.2	27.5	34.8	54.6
Roots	1.4	3.8	5.5	7.9	16.1
Magnesium					
Leaves	0.2	0.7	1.4	2.2	2.2
Living branches	0.1	0.4	1.7	2.7	4.4
Dead branches	0.1	0.2	0.4	0.8	1.0
Bole	1.8	3.3	5.6	7.4	10.5
Roots	0.5	1.4	3.0	3.6	4.6
Phosphorus					
Leaves	0.2	0.8	2.0	3.8	4.3
Living branches	0.2	0.6	2.2	2.1	3.4
Dead branches	0.2	0.2	0.4	0.6	0.8
Bole	0.8	1.7	3.0	3.6	6.2
Roots	0.4	0.8	1.6	1.7	3.9
Nitrogen					
Leaves	2.2	8.2	20.5	33.4	45.2
Living branches	1.4	4.3	13.9	16.5	27.5
Dead branches	2.3	3.3	5.6	9.4	13.7
Bole	5.5	13.4	22.5	29.7	47.6
Roots	2.1	6.3	10.1	13.5	28.8

a bole girth greater than the sampled range and only one tree with a bole girth smaller than the lowest value of the sample range.

Differences in the nutrient content of the tree stock estimated by the three methods reflect the dry weight differences, thus method (1) gives consistently low results but there is a general agreement between methods (2) and (3).

TABLE 6. The total oven dry weight (Kg/ha) of all trees by parts in the plot, calculated by three different methods (See text for explanation of methods).

Tree part	Method 1	2	3
Leaves	0.34	0.37	0.38
Living branches	0.63	0.70	0.72
Dead branches	0.43	0.49	0.47
Boles	5.94	5.94	6.03
Roots	1.47	1.63	1.64
Living trees	8.39	8.89	9.02

Distribution of Organic Matter and Nutrients

The weights of organic matter and of nutrients in the tree stock (calculated by method (2)) and in other components of the plantation are given in Table 7. The ground flora, mainly of wood sorrell *Oxalis acetosella*, was very sparse and plants were present in only 21 of the 400 quadrats. The estimate of rootlet weight is probably subject to considerable error since only eight soil cores were collected and sampling was restricted to the top 12.5 cm of soil, where the rootlets appeared to be most abundant.

Thirty-three years after planting, most of the organic matter in the plantation has been produced by the trees and is divided almost equally between living trees and dead material i.e. litter and dead trees. On average, organic matter has accumulated at the rate of 9,276 kg per hectare per annum. The current rate of accumulation is probably greater than this since the average value for the 33 years would be reduced by including the early period of low productivity when a closed forest cover had not developed (Ovington 1957, 1959).

The surface humus layer completely covers the mineral soil and is composed almost entirely of decomposing tree leaves and branches. The thickness of this layer varies greatly but it is about 12 cm thick giving a weight of 111,000 kg per hectare

TABLE 7. Distribution of organic matter and nutrients in the 33-year-old plantation of Pinus sylvestris *(Kg/ha).*

Item	O.D. weight	Sodium	Potassium	Calcium	Magnesium	Phosphorus	Nitrogen
Leaves	7300	3	43	36	6	9	89
Living branches	14000	2	39	30	7	7	52
Dead branches	9700	1	4	13	2	2	27
Boles	118800	—	84	115	24	12	97
Roots	32700	1	43	27	11	7	48
Rootlets	3400	1	11	6	2	4	33
Total for living trees	185900	8	224	227	52	41	346
Ground flora	10	<1	<1	<1	<1	<1	<1
Dead trees (exclusive of root system)	9600	1	1	6	<1	<1	9
Fresh litter (L)	2900	1	3	11	1	2	28
More decomposed litter (F + H)	107700	33	162	311	30	76	1594
Total	306100	43	390	555	83	119	1977

(standard deviation 29,600). The initial breakdown of the litter falling from the trees must be fairly rapid since the weight of fresh litter is equivalent to about a year's leaf fall. Compared with other woodlands (Ehwald 1957), the lowermost layer of more highly decomposed litter has tended to accumulate in excessive amounts probably as a result of the lack of thinning. The litter and dead trees contain a significant proportion of the total nutrients in the organic matter of the forest ecosystem, about 42 percent of the potassium, 59 percent of the calcium, 39 percent of the magnesium, 66 percent of the phosphorus and 82 percent of the nitrogen. If the litter were removed there would be a serious drain on the nutrient capital and conversely if litter breakdown was stimulated large amounts of plant nutrients would become available to the trees.

Tree leaves, branches and small rootlets tend to be short lived compared with the boles and roots which account for over 80 percent of the total dry weight of the living stock. If all the living tree boles were harvested, large amounts of plant nutrients would be removed amounting to about 22 percent of the potassium, 21 percent of the calcium, 29 percent of the magnesium, 10 percent of the phosphorus and 5 percent of the nitrogen contained in the organic matter of the plot.

Conclusions

Compared with agricultural, horticultural and aquatic crops, relatively little is known of the distribution and circulation of organic matter and plant nutrients in forest communities. Such information would be valuable in assessing the importance of site factors in controlling forest productivity and can also be applied to other problems for example, of forest site classification or of evaluating the gross role of the associated flora and fauna in the community dynamics. Inevitably, the sampling of forest ecosystems entails a considerable expenditure of effort so that it is important to develop sampling techniques which will give reasonably accurate results for the minimum expenditure of time.

The problem of determining the dry weight and nutrient content of a tree stand is complicated because of the diversity of tree size, the different proportions of leaf, branch, bole and root material in trees of different size and the different concentrations of nutrients in the tree components. The most accurate sampling method would be to sample a large number of trees covering the size range present in the stand and to determine regression equations relating dry weight and nutrient content to certain linear dimensions. This method is inevitably laborious, since all the trees in the stand have to be considered separately in arriving at the total weight of the stand. The technique of using sample trees for a range of size classes is not so accurate as the previous method but has the advantage of being relatively rapid. In some instances for example in sampling long-term experimental plots of small size, the number of trees that can be examined may be severely limited so that it is important to select the sample tree or trees carefully for both bole and canopy characteristics. The results obtained by this method can only be very approximate and the accuracy depends upon the uniformity of trees within the stand.

The paucity of the ground flora is unusual for a plantation of Scots pine at this age in Britain and reflects the density and dominance of the tree cover. Most of the organic matter in the stand has been produced by the trees and the build up of organic matter has immobilized significant amounts of plant nutrients, about 1 kilogram of sodium, 12 of potassium, 17 of calcium, 3 of magnesium, 4 of phosphorus and 60 of nitrogen per hectare per annum. The annual production of organic matter and uptake of plant nutrients must have been greatly in excess of these values for some decomposition of litter will have taken place.

Summary

1. The dry weights and nutrient contents are given for 20 sample trees of different sizes in a plantation of Scots pine.

2. The dry weight of the tree stock is calculated by three methods.
3. The dry weight and nutrient content of the tree stock, the dead trees, the ground flora and the humus layer in the sample plot are tabulated.

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